Russian Journal of Applied Chemistry, Vol. 77, No. 11, 2004, pp. 1765–1768. Translated from Zhurnal Prikladnoi Khimii, Vol. 77, No. 11, 2004, pp. 1783–1786.

SORPTION AND ION-EXCHANGE PROCESSES

Choice of Optimal Conditions of Chromatomembrane Mass Exchange in the Liquid–Gas System for Saturation of Aqueous Solutions with Oxygen

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Received July 23, 2004

Abstract—Fundamental aspects of the chromatomembrane mass exchange in the liquid–gas system are considered for the case of saturation with oxygen (oxygenation) of a physiological solution. The influence exerted by the geometrical dimensions and macroporous structure of a biporous matrix on the process efficiency is revealed.

At present, the membrane scheme of gas exchange is regarded as virtually the only possible way to remove gases from aqueous solutions and to saturate these solutions with gaseous components in flow-through analytical techniques [1] and as a unique principle of operation of blood oxygenators in medical practice [2–4]. However, this scheme has a common physicochemical disadvantage in all these cases, associated with the relatively low rate of molecular diffusion of oxygen across membranes. It is the limited rate of gas exchange across membranes that is responsible for the slow response of systems employed to monitor the composition of gases dissolved in water, for the need to use gas mixtures enriched in oxygen (compared with air) to saturate blood with oxygen, and for the insufficiently complete removal of carbon dioxide from blood in the course of oxygenation [4].

A scheme of mass-exchange processes in liquid–gas and liquid–liquid systems was suggested in the early 1990s as an alternative to diffusion membrane processes. This scheme was named the chromatomembrane mass-exchange (CMM) process [5]. It was demonstrated, already in the initial stage of investigations, that CMM can be, in principle, used for blood oxygenation [6, 7]. However, the problems associated with the efficiency of chromatomembrane oxygenation (CMO) and with the choice of optimal conditions of this process remained, on the whole, unsolved.

This study is concerned with fundamental aspects of the CMO process in model physiological solutions. Its goal is to determine the optimal porous structure of the mass-exchange bed and its geometrical dimensions and the best ratio of the flow rates of the liquid and gas phases.

EXPERIMENTAL

The scheme of the CMO process is shown in Fig. 1. The mass exchange between liquid and gas flows, which leads to saturation of the liquid with oxygen, occurs in a hydrophobic porous medium having the form of particles of porous polytetrafluoroethylene (PTFE), bound together in the course of repeated thermal annealing. Porous PTFE is formed in sintering of a PTFE powder formed in polymerization. Spaces between these particles constitute a system of open macropores along which moves an aqueous solution or, in the real oxygenation process, blood. The dimensions of these macropores can be arbitrarily varied by fractionation of particles of the porous PTFE obtained in the primary sintering. These particles contain open micro- and submicrometer pores comparable in size with particles of the polymerization powder. The micropores ensure the permeability of biporous matrices to air or gas mixtures. Biporous matrices are confined between the upper and lower microporous PTFE membranes impermeable to the liquid. The gas flow is fed into, and removed from, the microporous space of the matrices across these membranes.

The supply of the liquid into the micropores of the membranes and matrices is hindered by the capillary pressure arising because of the nonwettability of

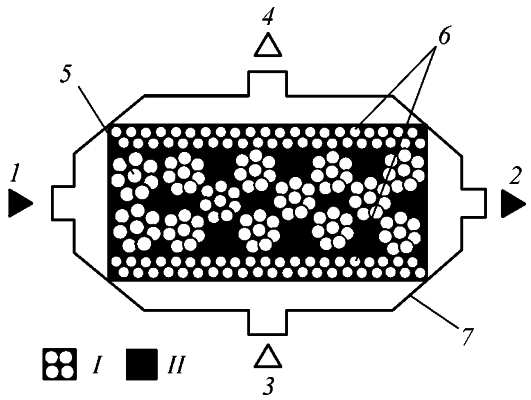

Fig. 1. Schematic of the chromatomembrane oxygenation process: (*1*, *2*) inlet and outlet of blood, (*3*, *4*) inlet and outlet of the air flow, (*5*) mass-exchange matrix, and (*6*) hydrophobic microporous membranes. (*I*) Microporous medium and (*II*) macropores.

PTFE with aqueous solutions and, in particular, with blood. In turn, the supply of the gas phase into macropores, in which the capillary pressure is negligible, is hindered by the pressure of the aqueous solution or blood filling the macropores. This pressure is maintained, according to the experimental conditions, at a higher level than the gas pressure. A more detailed information about the physicochemical principles and conditions under which chromatomembrane processes are performed can be found in [8].

The optimal conditions of the process, which would ensure the most effective saturation of the liquid phase with oxygen in CMM, were determined using the following physiological solution: 1 wt % NaCl + 4.5 wt % glucose. The physiological solution was passed through three in-series connected chromatomembrane cells (CMCs) with an independent feed of flows of the gas phase into each cell. The first CMC served for removing oxygen dissolved in the physiological solution with a flow of helium in order to determine the efficiency of the subsequent saturation of the solution with oxygen in the second CMC. It has been found previously that the CMO is more efficient than the conventional membrane scheme [6]. With account of these data, the physiological solution in the second cell was saturated with oxygen from the atmosphere, without its additional enrichment with oxygen. The third CMC was introduced into the hydraulic scheme to determine the degree of saturation of the physiological solution with oxygen in the second cell. For this purpose, a flow of helium was delivered into the third CMC through the line used to feed-in the gas phase. The flow of helium extracted dissolved oxygen from the physiological solution and then was directed into a gas chromatograph for analysis.

The results of a gas-chromatographic analysis were used to calculate, taking into account the fundamental aspects of CMM, the concentration c (mg l^{-1}) of oxygen dissolved in the physiological solution at the outlet of the CMC under study, using the formula

$$c = c_G W_L W_{G_0}, \quad (1)$$

where c_G is the concentration of oxygen in the flow of the extracting gas at the outlet of the third CMC according to gas-chromatographic data (mg l^{-1}); W_L, flow rate of the physiological solution through the chromatomembrane cells (ml min^{-1}); and W_{G_0}, flow rate of the extracting gas through the third CMC (ml min^{-1}).

The rates of gas flows through all the CMCs were varied with flow controllers and monitored using soap-film flow meters. The relative flow rate measurement error was ±1%. The flow rate of the physiological solution and blood through the CMC, W_L, was controlled with a peristaltic pump and measured with a measuring vessel and a stopwatch. The relative error in W_L measurements was ±1%.

The degree R of saturation of the liquid phase with atmospheric oxygen in the CMC under study was calculated by the formula

$$R = c/c_0, \quad (2)$$

where c_0 is the concentration of oxygen in water in equilibrium with air at a given temperature, known from reference data [9].

The biporous matrices of the CMC used in the study were in the form of parallelepipeds. The influence exerted on the efficiency of saturation with atmospheric oxygen by the ratio of the flow rates of the physiological solution and air through the CMC, by the dimensions of macropores in the biporous mass-exchange matrix, and by the length and height of this matrix was analyzed. The dimensions of the mass-exchange matrix in the directions of motion of the liquid phase and air and in that perpendicular to the first two were taken as length L, height H, and width, respectively.

The length and height of the matrices in the CMC under study, which are prototypes of chromatomembrane oxygenators, were varied from 20 to 100 mm and 10 to 30 mm, respectively, whereas the width remained constant (10 mm). The size of porous PTFE

particles constituting the matrix, which was taken as the macropore diameter, was varied in the range 0.25–1.5 mm.

The influence exerted by the ratio of the flow rates of air and physiological solution through the CMC on the degree of saturation of the latter with atmospheric oxygen is shown in Fig. 2. As expected, raising the flow rate of air through the CMC leads to an increase in the degree of saturation. In this case, the absolute values of the flow rates of air and the solution are unimportant and the degree of saturation depends only on their ratio. These data suggest that the maximum throughput of the CMC will be achieved at the maximum possible flow rates of the phases through the CMS, which are, in turn, determined by parameters of the porous structure of the biporous matrix. Degrees of saturation of the aqueous phase with atmospheric oxygen, equal to 95% and more, are easily obtained at a ratio of the flow rates of air and solution equal to 1 : 1 (and more).

The influence exerted by the length of the mass-exchange matrix on the efficiency of saturation of the aqueous solution with oxygen is illustrated by Fig. 3a. It can be seen that making the matrix and, accordingly, the CMC itself longer than 5 cm is virtually unfeasible because the degree of solution saturation changes in this case only slightly. The influence exerted by the height of the matrix is manifested in close association with that of its length. It was established that the height-to-length ratio of the mass-exchange bed, rather than the absolute value of the height, is of fundamental importance (Fig. 3b). It can be seen that the degree of saturation starts to decrease especially strongly when this ratio exceeds 0.5.

The size of macropores in the matrix affects the efficiency of saturation of the solution with oxygen only slightly (Fig. 4). By analogy with gas–liquid chromatography [10], this can be understood as follows: diffusion in the gas phase is the rate-determining stage of mass exchange. This circumstance makes reasonable use of CMC with coarse pores in chromatomembrane oxygenation to ensure high permeability of the mass-exchange bed to the liquid phase at minimum possible pressures, which rules out any damage to blood.

Thus, the optimal ratio of the flow rates of air and the liquid phase through the CMC is within the range 0.5–2. The height-to-length ratio of the matrix should not exceed 0.5; the sufficient length of the matrix is 50 mm; and, as shown previously [7], the width of the matrix affects the efficiency of mass exchange only slightly, and making it larger leads to a propor-

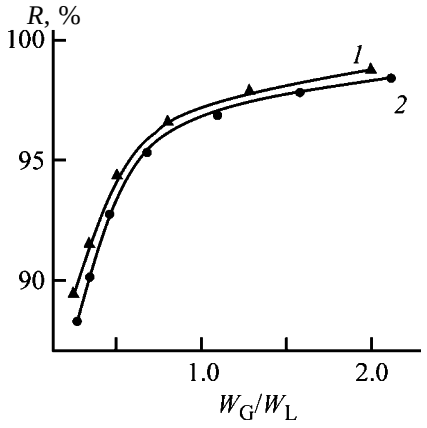

Fig. 2. Degree R of saturation of the physiological solution with atmospheric oxygen vs. the ratio of the flow rates of air and solution, W_G/W_L, through the CMC. Dimensions of the mass-exchange bed $30 \times 10 \times 10$ mm. Flow rate of the physiological solution (ml min^{-1}): (*1*) 5.0 and (*2*) 15.0.

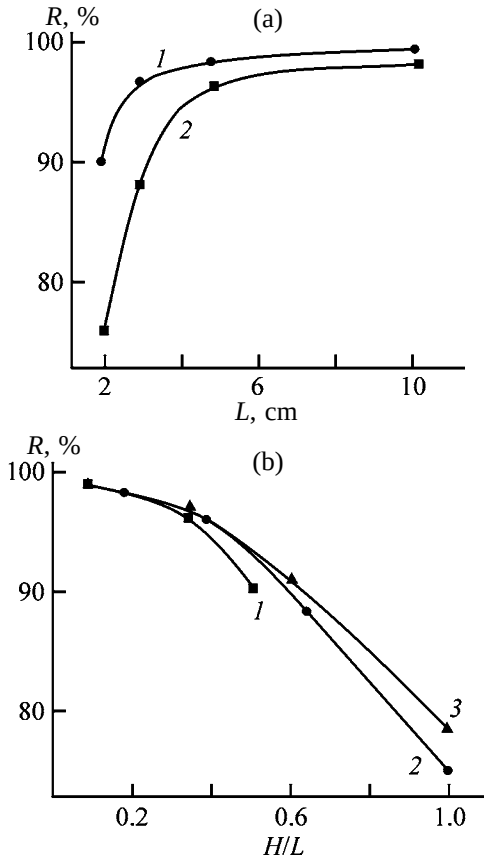

Fig. 3. Degree R of saturation of the physiological solution with atmospheric oxygen vs. (a) length L of the mass-exchange matrix of CMO and (b) matrix height to length ratio H/L. Height of the mass-exchange matrix (cm): (*1*) 1.0, (*2*) 2.0, and (*3*) 3.0.

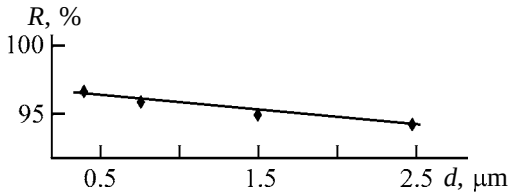

Fig. 4. Degree *R* of saturation of the physiological solution with atmospheric oxygen vs. size *d* of macropores in the matrix. Flow rate of air and solution 5 ml min^{-1}; length and height of the mass-exchange matrix 3.0 and 1.0 cm, respectively.

tional increase in the output capacity of the CMM process.

The results of experiments performed with donor blood on the same CMC and at the same flow rate ratios of blood and atmospheric air confirmed that, as in the case of physiological solutions, the prototype chromatomembrane oxygenators ensure higher efficiency of oxygenation than that obtained with their membrane analogues.

CONCLUSION

The size of macropores in the biporous mass-exchange matrix has virtually no effect on the efficiency of chromatomembrane oxygenation. The optimal ratio of the flow rates of air and the liquid phase being oxygenated across the mass-exchange bed is within the range 0.5–2. The aqueous phase is saturated with oxygen to virtually the equilibrium extent if the dimension of the mass-exchange bed in the direction of its flow exceeds by a factor of at least 2 that in the direction of flow of the gas phase.

ACKNOWLEDGMENTS

The authors thank the Russian Foundation for Basic Research (project no. 03-03-32328) for support of this study.

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